Altitude-dependent changes of directional hearing in mountaineers

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This study demonstrates apparent deterioration in the ability to localize sound associated with acute exposure to high altitude in ten subjects on three mountaineering expeditions. Furthermore, the auditory localization errors improved to sea level values after a period of acclimatization. Occurring at altitudes where overt neurological symptoms are not usually seen, impairment of sensory perception may explain the increase in accidental deaths associated with altitude exposure due to disorientation and misjudgment but before hypoxia is evident.

Keywords: Mountaineering, altitude hypoxia, auditory localization, acclimatization

Casualties among mountaineers, caused by objective dangers such as avalanche are in many instances believed to be the direct result of disorientation and misjudgment brought about by hypoxia. One of the overt effects of hypoxia is Acute Mountain Sickness (AMS) – a syndrome of insomnia, anorexia, headache, fatigue and nausea which sometimes may develop into fatal high-altitude cerebral and/or pulmonary oedema. AMS occurs in varying degrees at 3000 m and above. At lower altitudes, however, and even at those high altitudes, experienced mountaineers may feel themselves in full possession of their faculties. We ask whether such confidence is justified.

In this study we set out to investigate the effects of altitude on auditory functions involved in orientation of head and body. Disturbance of these mechanisms might be expected to impair the ability to react appropriately in hazardous circumstances. We have concentrated on one aspect, namely directional hearing, and have employed a portable test to assess the accuracy of auditory localization as a function of altitude and acclimatization. In this account we present observations from three mountaineering expeditions.

Subjects and methods

Subjects
Ten men aged 20–30 years took part in this study, seven on one expedition only and three on two of the expeditions. All subjects were experienced climbers but with limited experience of high-altitude mountaineering. All of the subjects reported normal hearing in both ears. This was confirmed in nine of them on the basis of pure tone thresholds measured either in the laboratory, before and after the trip (Himalayan expedition), or in the field, with specially prepared test tapes (Andean expedition).

Expeditions
The experiments were carried out during the 1988 British Janaonli expedition in the Himalayas (five subjects), the 1989 Sheffield Peruvian expedition (five subjects) and during a climb in the French Alps, Mont Blanc (three subjects).

Environmental conditions for tests
Auditory testing was carried out mainly in the open air (Andes, Alps) or in a tent (Himalayas). Subjects were comfortably clad and relaxed during the performance of the tests, despite low ambient temperatures. Noise levels from wind and other sources were generally low, particularly at the higher altitudes, and therefore favourable for auditory testing.

Preparation of the hearing test
Auditory localization was assessed by means of simulated directional stimuli reproduced from binaural tape recordings. We have found that this method provides reproducible values for individual characteristics. The tapes were prepared in an acoustic chamber using a dummy head microphone system. (This method retains the original directional information). On replay over headphones, sound is perceived in the space around the listener from directions generally corresponding with the original source locations. The sound stimuli used to prepare the tapes consisted of trains of 0.5-s bursts of wide-band noise presented at a repetition rate of 1 s⁻¹ from a loudspeaker mounted on a mobile boom.
Altitude and directional hearing in mountaineers: M. E. Rosenberg and A. J. Pollard

Sequences were recorded in which stimuli were applied from 90 or 100 different directions, one at a time, encompassing 360° in the horizontal plane. Each stimulus presentation was preceded by verbal statement of an identification number. The order of presentation from different directions was randomized.

Conduct of the test
The subject (on the mountain) listened to the recording with headphones using a personal stereo machine (Sony Walkman or equivalent) and was instructed to respond in each stimulus presentation by marking the perceived direction of the sound along with the identification number on a circular chart. Subjects were not required to complete all 90 or 100 test items (see Results section). Different test sequences were used on different expeditions, but the same one was used throughout any given expedition.

Analysis
The angular values of the responses were measured by protractor and listed against the original locations of the source. Localization errors were derived by subtraction. We defined localization error as the absolute (unsigned) difference in degrees between source position and response. Probability values given in the Results section were obtained by two (independent) sample t tests.

Exclusion of data
As in other studies of directional hearing, we found that sounds originally presented from a frontal location sometimes appear to come from behind the listener (and to a lesser extent vice versa). For this reason we have not included values for sounds presented from the front quadrant when calculating the mean directional error. Each error value given below is therefore the mean for stimuli in the left, right and rear quadrants.

Results
Time course of exposure to altitude
Figure 1 and Figure 2 give the sequence of sampling for the major expeditions. The altitudes at which tests were conducted are indicated. It can be seen that the climbers experienced continuous exposure to altitudes of 3000 m or more for up to 30 days. With such durations it must be assumed that significant acclimatization had occurred. Accordingly, we have distinguished between early and late stages of the expeditions. The severity of the hypoxia encountered in this study did not produce overt neurological symptoms in our subjects, all of whom appeared to be in normal spirits at the times of testing.

Figure 1. Sequence of the Andean expedition. Arrows indicate the altitudes and times at which testing was carried out and the number of subjects tested. Dashed lines give an alternative climbing schedule followed by some members of the team.
Altitude and directional hearing in mountaineers: M. E. Rosenberg and A. J. Pollard

Figure 2. Sequence of the Himalayan expedition. Explanation as for Figure 1

Andean expedition

Table 1 gives individual values for a pair of climbers who carried out similar programmes of tests. At 3400 m, tested after 1 or 8 days, there was no systematic change in auditory localization compared with that at sea level, but at 4200 m, and tested soon after arrival, localization in both climbers had worsened. Further slow ascent (with 9 days to acclimatize) did not cause further deterioration. An additional rapid ascent, however, caused substantial acute deterioration. Figure 3 is an attempt to summarize the results from all members of the expedition by grouping combined data. Acclimatization is evident during the stages of slow ascent, and deterioration is evident after further rapid ascent.

Himalayan expedition

The grouped data (Figure 4) indicate significant deterioration in auditory localization on initial ascent to only 1000–2000 m. However, with accumulating exposure time and despite further ascent, there was improvement of performance back to the sea level values.

Alpine expedition (Figure 5)

In this expedition the subjects made two ascents above 1000 m each lasting about 2 days. It was found, in the short term, that auditory localization was significantly poorer at the higher altitudes.

Motivation

In a field study such as this, carried out under conditions of substantial physical endurance, it is important to consider the effect of motivation. A relevant quantity is the response rate, here defined as the number of individual test items voluntarily attempted by a subject in a test session containing 90 or 100 such items. In the event we found this number to be similar at the different stages of a given expedition (see legends to Figures 3–5), suggesting that motivation to perform the test was unaffected by altitude. Higher response rates were returned for the Andean expedition than for the (earlier) Himalayan expedition. This was due to an express instruction to

<table>
<thead>
<tr>
<th>Altitude (m)</th>
<th>Stage of climb (days)</th>
<th>Localization error (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Climber 1</td>
</tr>
<tr>
<td>0</td>
<td>1/−2</td>
<td>22.73 (1.80)</td>
</tr>
<tr>
<td>3400</td>
<td>1/8</td>
<td>24.07 (3.33)</td>
</tr>
<tr>
<td>4200</td>
<td>9</td>
<td>27.30 (3.16)</td>
</tr>
<tr>
<td>4825</td>
<td>18/20</td>
<td>26.64 (2.77)</td>
</tr>
<tr>
<td>5360</td>
<td>28</td>
<td>40.14 (3.95)</td>
</tr>
<tr>
<td>4825</td>
<td>30/34</td>
<td>23.86 (2.61)</td>
</tr>
</tbody>
</table>

Values are mean(s.e.m.) for individual tests

Br J Sp Med 1992; 26(3) 163
Altitude and directional hearing in mountaineers: M. E. Rosenberg and A. J. Pollard

Figure 3. Auditory localization at altitude – adaptation and acute exposure. Data from the Andean expedition has been grouped according to early, intermediate and late stages of the expedition. Each column represents the mean error(s.e.m), mean altitude and mean time of exposure. Note that localization errors declined during slow ascent but were raised again on acute exposure to 5360m (P < 0.001). (Sea level values have been omitted because only two of the subjects were tested at this altitude but are included in Table 1.) Data obtained at different altitudes have been combined in the first three columns. In the fourth column all data were obtained at the same altitude. Mean altitude, A, was derived as follows:

\[ A = \frac{1}{N} \sum (n_1a_1 + n_2a_2 \ldots n_2a_2) \]

where \( n_1, n_2 \) etc. are the numbers of observations (individual test–response trials) in separate test sessions, \( a_1, a_2 \) etc. are the corresponding altitudes and \( N = n_1 + n_2 \ldots + n_2 \). The mean time of exposure was derived in the corresponding manner. Mean response rate (including frontal stimuli) = 81, 89, 89 and 84 responses per subject per test session for days 2, 13, 26 (4821 m) and 26 (5360 m) respectively.

Figure 4. Auditory localization at altitude – acute exposure and adaptation. In this result, from the Himalayan expedition, note the increase in the magnitude of errors on first exposure to altitude (P < 0.001) and the decrease to sea level values during the subsequent (slow) ascent. Mean altitudes and times of exposure were calculated as in Figure 3. Mean response rate = 51, 23, 23, 25 responses per subject per test session for sea level, days 2, 11 and 21, respectively.

Figure 5. Auditory localization at altitude – acute exposure. Localization was measured on Mont Blanc during two ascents within a period of 7 days. Each climber undertook the test at 4300 m and at two or three lower altitudes. Note that errors were significantly greater at the higher altitude (P < 0.01). Mean response rate = 38 and 30 responses per subject per test session for 2470 m and 4300 m, respectively.

the participants to attempt more of the test sequence. The finding that they were able to adhere to this instruction throughout suggests that a high level of motivation was sustained at all stages of the expedition.

Pure tone thresholds

In the expedition to the Andes, subjects measured their relative pure tone thresholds in order to investigate differential frequency sensitivity. No changes were found during the gradual ascent to 4800 m, but on brief exposure to 5360 m there was significant elevation of thresholds (mean, 14 dB) in the range 3000–8000 Hz compared with the range 125–2000 Hz.

Discussion

Employing a portable binaural test, we have measured performance in a simulated auditory localization task in mountaineers during three climbing expeditions. We observed significant deterioration of apparent localizing ability on arrival at a higher altitude and progressive improvement with continued exposure. An acute effect was evident even at altitudes as low as 1000–2000 m (Himalayas), and therefore below the altitudes usually associated with symptoms of mountain sickness.

Audimetric conditions were favourable, subjects were in thermal comfort despite low ambient
temperatures, and motivation in the performance of the tests, inferred from response rates, appeared not to be significantly affected by altitude. Other variables, including fatigue and emotional distractions, were not assessed but any influence due to these causes would probably have affected response rate. The remaining altitude-dependent variable is PO2. We therefore attribute deterioration in performance of the tests to hypoxia, and subsequent improvement to the process of acclimatization.

The lowest altitude associated with an effect (assuming it to be dependent on the reduction of PO2 below some critical level) is presumed to be influenced by regional and seasonal fluctuations of atmospheric conditions – a 12% change in barometric pressure, in free air, would be equivalent to an altitude difference of around 1000 m (Reference 6). While this relationship does not hold precisely on mountains, it does serve as a guide to relative changes. In order to judge whether our three expeditions are directly comparable in terms of altitude versus PO2, we have consulted the meteorological data from the geographical regions of the appropriate periods (UK Meteorological Office, Bracknell, personal communication), these reveal that pressure was stable for the duration of all three expeditions. In each case the maximum and minimum values for the daily average were within 0.5% of the mean for the whole period. The mean pressures, normalized to sea level values, were almost identical for the three regions, differing by less than 1% over the periods in question. We conclude that the relationship between altitude and PO2 was similar for all three expeditions.

Concerning the physiological explanation, it should be considered whether the effects are indeed on auditory perception per se, for it is conceivable that the observed deterioration lies in the motor response to the stimuli (i.e. marking the direction of sound on the chart). However, errors of eye–hand coordination are normally more than an order of magnitude smaller than those of auditory localization, and although they might rise under the circumstances of the investigation, this is unlikely to be a major factor in the observed changes. The effects could be peripheral or central in origin – an effect on auditory peripheral function is suggested by the apparent high-frequency loss found in one of the expeditions. Such a change would be caused by selective reduction of the oxygen supply to the basal part of the cochlea and is consistent with a deterioration in the perception of auditory localization. Alternatively, or additionally, the effects on localization might have a central auditory cause, in which case they may indicate general worsening of cerebral performance.

In conclusion, we have found that exposure even to moderate altitudes caused acute deterioration in at least one of the sensory modalities involved in human orientation. Possibly other aspects of motor and sensory coordination also were affected. If such changes go unrecognized, they are likely to increase the degree of personal hazard. These circumstances may have contributed to previously unexplained accidents involving experienced climbers.

Acknowledgements


References

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